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THERMAL AND STRESS CHARACTERIZATION OF VARIOUS THIN-DISK LASER CONFIGURATIONS AT ROOM TEMPERATURE

William P. Latham, et al.

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Interim Report

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Thermal and Stress Characterization of Various Thin-disk Laser Configurations at Room Temperature

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ABSTRACT

Operational performance of kilowatt-class thin-disk ceramic and single crystal Yb:Yag lasers is presented. High pump power is applied to various thin-disk assemblies on two different test beds. The assemblies are composed of ASE caps, 200µm gain media, and heat sinks made of SiC, sapphire, or diamond. A novel mounting and cooling process is described.

FEA modeling of the assemblies is performed using COMSOL stress and thermal computations to understand and quantify thermal and stress effects on beam quality and laser output power. Under increased pump power, the thin-disk can deform 5-10 µm in the center, destroying cavity stability. This is observed experimentally. The results of this work indicate that a single thin-disk laser could simultaneously produce high beam quality and high power if novel thermal management techniques are employed.

Keywords: Laser materials; Lasers, ytterbium; Lasers, solid-state; Lasers, diode-pumped; Optical materials

1. INTRODUCTION

Thin-disk lasers have shown impressive power generation in the multi-kilowatt levels for single disk resonators and nearly 30 kW for multiple disk resonators since the invention in 1992. Single crystal Yb:YAG thin-disk lasers (TDL) now operate at kW powers with greater than 60% slope efficiencies and "wall-plug" efficiencies more than 20% [1, 2, 3]. While single crystal materials produce outstanding results, a new alternative is the use of ceramic materials. Highly translucent and low scattering ceramic materials have been produced using purely chemical reactions and nanocrystalline powder sintering in vacuum ovens[4,5]. Large diameter polycrystalline Yb:YAG can be used for area scaling of single thin-disk lasers. Spectroscopic and laser characteristics of ceramic Yb:YAG are very similar to those of single crystal. Low power laser results with ceramics have been quite promising with greater than 60% slope efficiency[6]. Taira et al. demonstrated output power intensity of 3.9 kW/cm^2 from a composite all-ceramic Yb:$Y_3Al_5O_{12}$ microchip laser with the maximum thermal stress exceeding twice the tensile strength of single crystal[7]. Latham et al. reported 6.5 kW output power from a single thin-disk ceramic laser, which is, to our knowledge, the highest power obtained from a single disk[8].

One of the requirements for directed energy applications is the need for laser beams with a very high, practically Gaussian, beam quality. Thin-disk lasers suffer in this respect. Their development and commercial application has been directed mainly towards laser welding where the relatively poor beam quality is not detrimental. Several different factors are responsible for poor beam quality. The one that has become the focus of this research is associated with the effects of the high heat load generated in the YAG media. There are several sources of heat generation and the chief culprit is associated with the quantum defect between the 940nm pump and 1030nm lasing light. In addition, spurious generation of amplified spontaneous emission takes place. The fraction of this light that is reabsorbed in the media also generates a heat load. Finally, excess absorption of light due to multiple causes (color-centers, defects in the YAG,

bonding layers, etc.) adds to the problem. Much of this research was established to investigate methods to mitigate these issues.

In this report, a novel thermal management technique in Yb:YAG ceramic TDL is shown. Our results illustrate that polycrystalline Yb:YAG ceramic thin-disk geometry has a strong potential for operation at multi-kW output level. Performance and beam quality are limited in part by the thermal issues inherent to multi-kW pumping and the cooling methods incorporated. These subjects are investigated via experimental measurements and numerical modeling.

2. EXPERIMENTAL WORK

Yb:YAG Material and Assemblies – Large Test Platform

Yb:YAG ceramic thin-disks used are manufactured by the Konoshima Corporation (Japan). The disks are 200 µm thick and Yb- doped at 9.8%. The diameter is 35-37 mm. Disks used in initial high power studies are diffusion bonded to a 1 mm undoped YAG ceramic. The undoped cap serves two purposes. Primarily it aids the suppression of amplified spontaneous emission generated. By being index matched a significant fraction of the spontaneous emission escapes upward through the undoped cap rather than total internally reflected within the Yb:YAG material. The second reason for the undoped cap is to provide rigidity. Without the cap, a 0.2 mm thick Yb:YAG disk will immediately disintegrate when subjected to the water jet impingement cooling. The bonding process of Yb:YAG to YAG is performed by Precision Photonics using their chemically activated direct bonding (CADB) technique. The top side of the thin-disk assembly is coated with a dichroic anti-reflection (AR) coating. The bottom side of the assembly is coated with a high reflective (HR) coating at both the 940 nm pump and the 1.03 µm laser wavelengths.

The YAG assemblies are either attached to heat sinks or directly to the CuW cooling mount, see Fig. 1(b) & (c). The heat sinks tested are SiC, sapphire, and diamond all with a thickness of 0.5mm. The Yb:YAG/YAG assemblies are attached to the submounts either using an epoxy (for diamond and SiC) or the CADB process (Sapphire). The finished unit is epoxied to a CuW holder around the periphery. With the CuW unit, 26 mm clear aperture is available to pump. Pump spot diameter used is 18 mm. The back side of the assembly is then cooled by a water spray. In this work, cooling of the Yb:YAG or heat sink is accomplished by jet-impingement cooling, 2.5 gal/min at 20 ^{o}C, directly against the back of the disk assembly.

Since the submounts provide sufficient mechanical rigidity to withstand the water pressures of the cooling spray, the opportunity to examine laser performance without the undoped YAG cap is created. Thus some of the Yb:YAG samples are mounted to the heat sinks without an undoped YAG cap. This provides an opportunity to examine the deleterious role of amplified spontaneous emission.

Experimental Setup

Figure 1 describes the laser cavity and thin-disk assembly. In Fig. 1(a) a straight-forward „I" laser cavity is built in which the other end of the cavity is a concave output coupling mirror. The main thin-disk chamber contains the Yb:YAG media, multi-pass reflecting mirrors for the pump, and cooling. In the figure, M refers to highly reflective mirrors, OC is the output coupler mirror, 2 m radius of curvature and coated for 87% to 99% reflectivity at 1030 nm. The path of the pump light is portrayed by the narrow dotted lines. The laser light is indicated by the double dotted lines. The pump mirrors are water cooled. The Yb:YAG assembly is water jet impingement cooled. The bottom surface of the Yb:YAG is HR coated so as to define one end of the laser resonator cavity. During the experiment, along with the usual power measurements, a thermal camera and Silicon CCD camera film the ramp up to full power. Figure 1(b) is a photograph of a mounted disk assembly, and Fig. 1(c) is a CAD drawing of the assemblies side view.

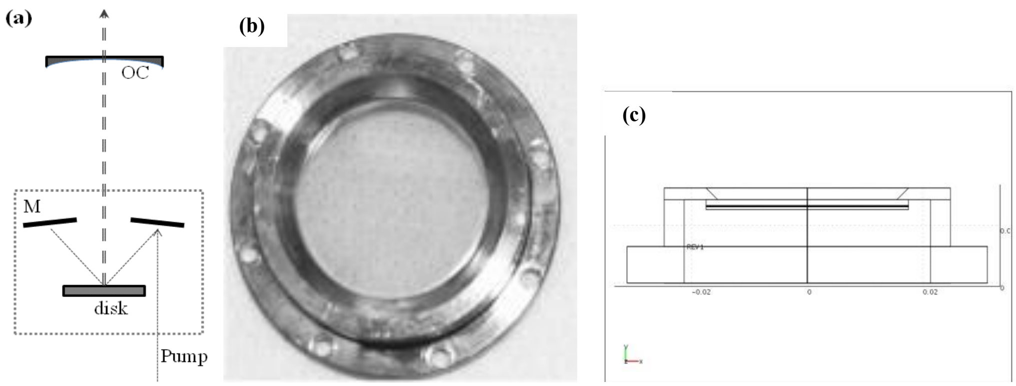

Figure 1 Experimental Arrangement (a) I-cavity, (b) 35 mm mounted disk assembly, (c) CAD drawing of thin-disk assembly

The 940 nm laser diode pumping system consists of six Jen-Optics 2.5 kW/25 bar-stack laser diodes with collimating spherical-cylindrical lenses, combined using a thick polarizing plate and homogenized in a 20 cm SupraSil rod providing 12.7 kW of maximum pump power. The output of the homogenizing rod was relay-imaged to produce a fourth order super-Gaussian pump profile. The pump beam is re-imaged eight times on the thin-disk using a parabolic mirror insuring 90% absorption of the incident pump power during lasing. It was observed that the thin-disk (TD) pump absorption saturates to 80% of the incident pump power in fluorescence (non-lasing) mode, with a blocked cavity mirror.

Thermal lensing

A fluid flow/thermal conduction simulation (using cfDesign software) of the jet impingement cooling nozzle showed strong transverse variation of the water velocity and film coefficient. The results are shown in Figure 2. This translated to temperature variations of up to 40^o C for a heat load of 0.8 kW/cm^2 between points directly cooled and locations in between jets. The simulation points to complete washout of this transverse temperature variation, through radial heat conduction, in the interior of the undoped cap, in agreement with thermal camera images of the undoped cap (not shown). The pump induced nozzle thermal imprint is fully developed at a distance of ~ 30 cm away from the disk. This pattern complicated proper wavefront characterization.

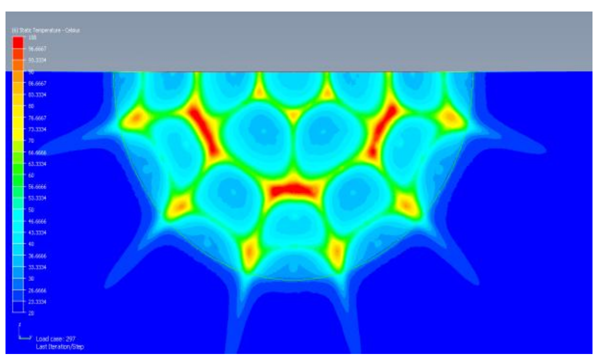

Figure 2 CFD Simulation

Thermal lensing of the lasing disk is measured by an expanded and collimated 980 nm fiber coupled semiconductor laser probe (7 mm diameter). The beam far-field profile was imaged on a camera 2.2 m away from the thin-disk. Three thermal lensing contributions were identified; (1) thermal expansion induced negative lensing (disk acquiring a convex radius of curvature), (2) positive lensing due to the temperature profile towards the pump spot edge, and 3) a thermal imprint of the cooling nozzle. The far-field profile of the 7mm diameter probe beam reflecting off of the unpumped disk is shown in Fig. 3 (a). Figure 3(a) is the baseline image. Figures 3 (b) and (c) show the probe near-field profile off of the

pumped disk for the 18 mm pump spot of equal pump intensity, respectively. Thermal expansion induced negative lensing and the nozzle imprint is clearly demonstrated for the large pump spot in Fig 3 (b) for the disk without the heat sink . The images are looking at the surface, see Fig. 1(b) for a visual reference. Positive lensing due to the pump-edge temperature profile is highlighted in the intense ring and smaller probe beam in Fig 3 (b). It is worth pointing out that thermal expansion induced disk flexure scales with the total pump power and not with pump intensity.

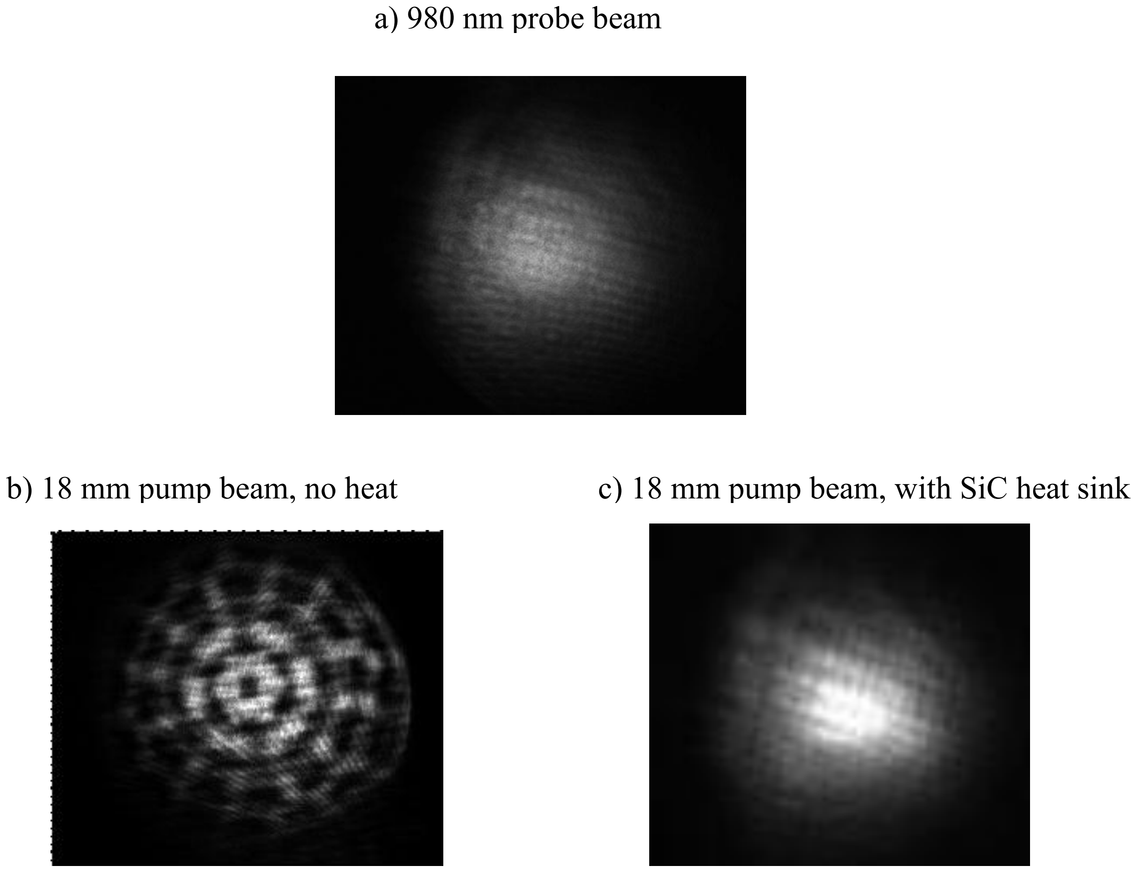

Figure 3 (a) Far field profile of a 7 mm diameter 980 nm probe beam reflecting off of the unpumped disk, pump spot images (b) without and (c) with SiC heat sink

It is possible that the preferential cooling of the disk in Figure 3 (b), may be alleviated by a redesign of the water cooling impingement mechanism. Furthermore, the effect this will place on the heat removal capacity hasn‟t been examined. But the use of the intermediary heat sink improves the outlook. Figure 3 (c) shows the probe beam from a disk assembly that is mounted onto a SiC submount. All evidence of the nozzle imprint is alleviated in this case.

Cap temperature in lasing and ASE modes.

The temperature of the undoped cap, as measured by a thermal camera, was systematically higher in the lasing mode than during nonlasing/fluorescence mode (blocked cavity). The dependence of this excess heating on the output coupling percentage indicates the temperature increase is proportional to the intracavity intensity level. The rate of temperature increase with respect to the *absorbed* pump intensity is 23.8^{o}C/(kW/cm^2) in fluorescence mode and 27.2^{o}C/(kW/cm^2) in lasing mode for the linear cavity with 4% output coupling and reaches 35.1^{o}C/(kW/cm^2) with 1% output coupling. These estimates take into account the pump absorption saturation (reduced absorption) in the fluorescence mode. Assuming a temperature gradient in the doped region and a constant temperature throughout the undoped cap, the fluorescence mode temperature increase implies that 12% of the absorbed power is dissipated as heat which is close to the 11% quantum defect. With power extraction in the lasing mode, we expect a lower temperature, since more of the deposited energy leaves the TD in the laser output beam. The undoped cap temperature reached 185^{o}C for the maximum output power of

6.5 kW. This excess heating at the AR coating, imposed a lower (upper) limit on the pump spot size (pump and extracted power intensity) and therefore necessitated the use of a larger pump size to fundamental cavity mode size ratio.

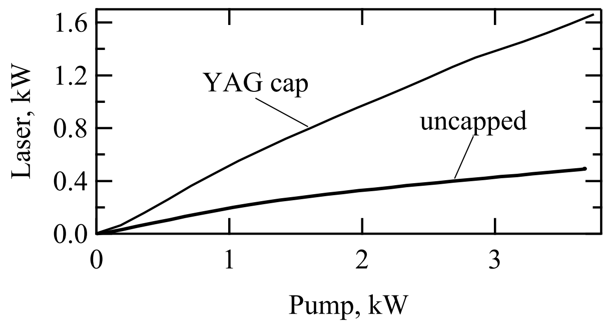

Figure 4 Laser power curves for YAG/Yb:YAG and uncapped Yb:YAG samples

Performance between YAG capped and un-capped Yb:YAG material.

With the availability of heat sinks to provide structural stability, Yb:YAG lasing can be examined with and without the undoped YAG caps. In this case, the result is striking. For the tests presented here, the particular material used in both cases is similar, but unfortunately not of high quality. Although disks were mounted upon diamond heat sinks, the vendor inadvertently used a thermally insulating epoxy for attachment. Still, the fact that the two samples are identical allows a direct comparison to be made. The disk diameter is 35mm with a clear aperture of 25mm. Figure 4 shows the laser power versus pump for the two cases. The capped disk develops a slope efficiency of 40% but this is substantially greater than the uncapped sample, which only exhibits 20%. Furthermore, the latter‟s slope efficiency turns sub-linear at higher powers.

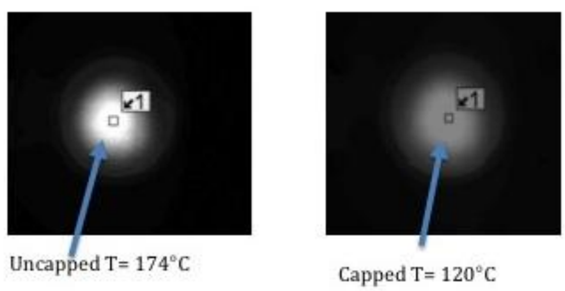

Figure 5 Surface temperatures at 3.7kW (a) YAG/Yb:YAG, (b) uncapped Yb:YAG

In Figure 5, thermal images are shown of both disks. The central 18mm of each disk is pumped with 3.7kW power. Figure 5 (a, left) is the YAG capped sample. It reaches a maximum temperature of 120 C. Figure 5 (b, right), the uncapped sample, excessively heats to a much higher temperature at 174 C. Although there may be differences in the number of material defects, the primary difference contributing to the rise in temperature is the ASE amplification and re-absorption within the disk.

Yb:YAG Material and Assemblies – Small Test Platform

Our thin-disk lasers have been operated at room temperature with water jet impingement cooling. However there are a number of limitations with this scheme. For one, jet impingement produces a severe phase distortion on the beam and reduces the useful gain area as seen in Figures 2 and 3. Second, there is only limited temperature control of the jet spray, and obviously cryogenic cooling is not feasible. Hence in addition to the large cavity laser we have built a smaller thin-disk laser cavity. The water jet impingement cooling is replaced by a custom sealed spray nozzle and mounting cap design. The new cooling setup, manufactured by the Rini Corp. (Orlando, FL), utilizes a two-phase spray boiling technology. Two cooling versions have been acquired. The first operates with R134 refrigerant, and the second utilizes LN2 for cryogenic operation. This technology provides much more uniform cooling than water impingement, and should improve both the phase distortion and the power extraction. The laser is pumped with 1kW of 940nm fiber delivered pump light. The pump is imaged for 12 double passes on the thin-disk. Figure 6 shows the expanded view of the test platform with pump beam path. These experiments enable testing with multiple thin-disk configurations to compare thermal distortion effects and power extraction capability. The future tests with good disks will require measurement of laser wavefront, power extracted and temperature rise in the thin-disk, as well as detailed analysis of ASE and optical spectrum.

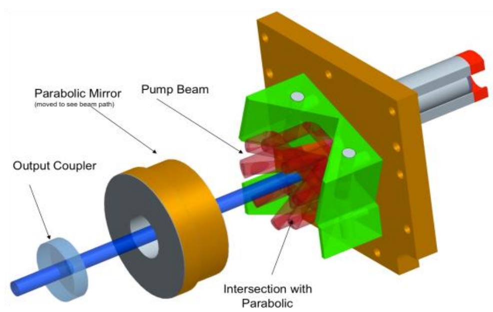

Figure 6 Small test platform

The spray system requires that the thin-disk be attached to the mounting cap over its entire area, which is a non-trivial endeavor. An initial process was developed in which the gain material was attached to the cap using thermally conductive epoxy and then evacuated in a vacuum chamber. Still voids and uneven bond lines ensued. An alternative process using flux-less Indium solder was developed by Precision Photonics (Boulder, CO) and Enerdyne Solutions (North Bend, WA). Major challenges including elimination of voids in the solder layer, delamination due to poor adhesion of the layers and disk edge chipping have been overcome. There is also a problem with CTE mismatch of different heat sinks and the CuW cap. Special polishing, cleaning and handling procedures had to be developed to handle the disks. Ultimately this new process has demonstrated very thin and even bond lines with the absence of solder voids. Figure 7 shows several test examples of the Indium soldering.

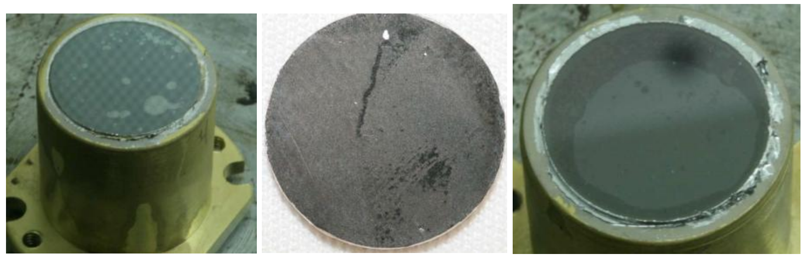

Figure 7 Test sample of soldered thin-disks

3. NUMERICAL MODELING

Concurrent with the experimental inquiry, analytical and numerical techniques are employed. For the numerical approach, COMSOL Multiphysics is used. COMSOL is commercial software that applies numerical techniques based on the finite element method for the spatial discretization. The disk geometry along with the appropriate material constants are programmed. Cooling is assumed to be constant across the bottom surface of the disk. This is unlike the real situation where cooling is via spray jets. But it is sufficient to compute the overall disk deformation and surface temperatures. The model does include thin layers such as the epoxy layer that is necessary to attach SiC and diamond to the HR coatings on the Yb:YAG.

The high power laser described above, without heat sink component and described in Fig. 2, ultimately succumbed to cavity instability. Using absorbed pump powers based on the maximum observed laser power, 890W, along with estimated thermal transfer coefficients, $5x10^4$ W/m^2K, the deformation and surface temperatures are computed. Figure 8 shows the surface temperature and deformation of the disk across its diameter. The disk‟s expansion is checked by the cooler stiff CuW cap that forces the disk curvature to change. The deformation shows several waves of sag at the edges. A complete computation of the wave front would have to include contributions to the refractive index from the temperature variation across the disk.

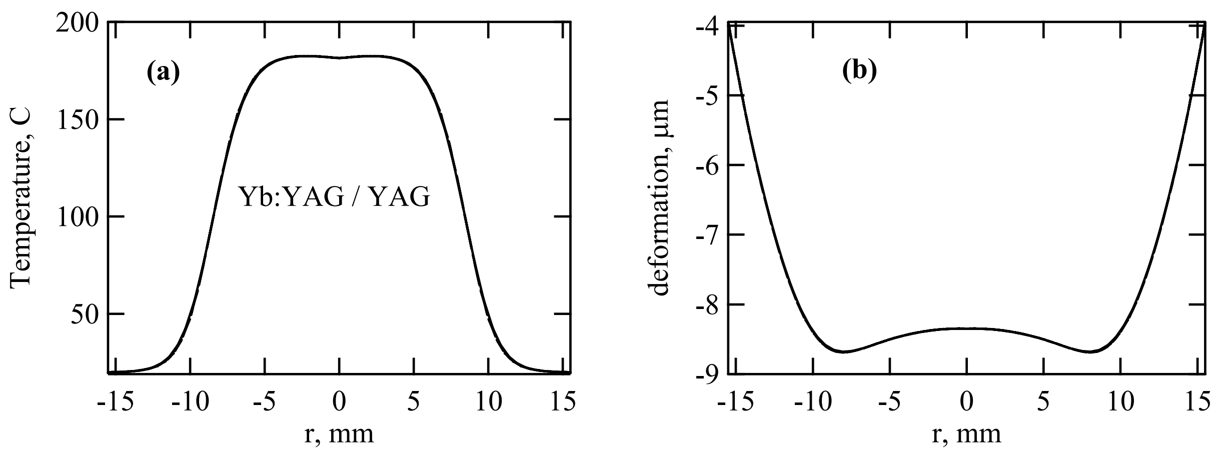

Figure 8 (a) Computed surface temperature Yb:YAG/YAG (b) Computed disk deformation across the diameter of the disk under a severe heat load

The surface temperature of the disk assembly is computed for various cases. Figure 9 shows the heating for the case of the capped YAG-Yb:YAG and the uncapped Yb:YAG sample, see the experimental data shown in Figs. 5 and 6. COMSOL by itself is unable to theorize the heating due to ASE. Our model accounts for ASE heating increasing the heat load until the model agrees with experiment. This increase is a 1.75 factor for the capped disk and a 2.75 factor for the uncapped disk. As seen experimentally, the laser slope efficiency suffers since thermally energized electrons incresingly populate the lower lasing level.

Finally Fig. 10 plots the surface temperature of the disk assembly under a 500W heat load, when incorporating a heat sink. The case of SiC and diamond is shown. Diamond possesses a thermal conductivity nearly 5 times greater than that of SiC. However, in revenge, the thermal expansion coefficient of SiC is much closer to that of Yb:YAG than that of diamond, which will be of significance if extreme thermal cycling is expected.

The idealized model scenario only exists when the material, optical coatings, and attachment techniques are perfected. These are engineering challenges that can be overcome. The more fundamental problem to attack lies with the inevitable ASE production in the Yb:YAG. This is difficult to theoretically predict.

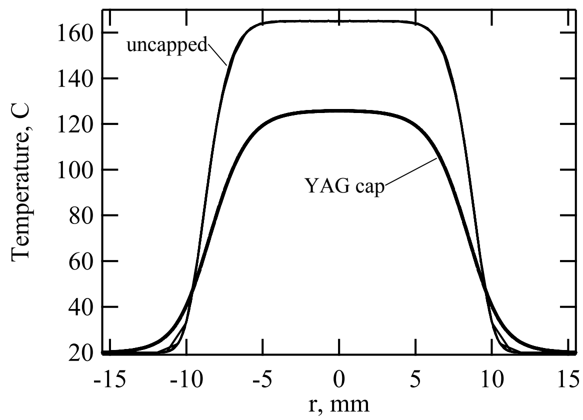

Figure 9 Surface temperature across disk for capped and uncapped samples

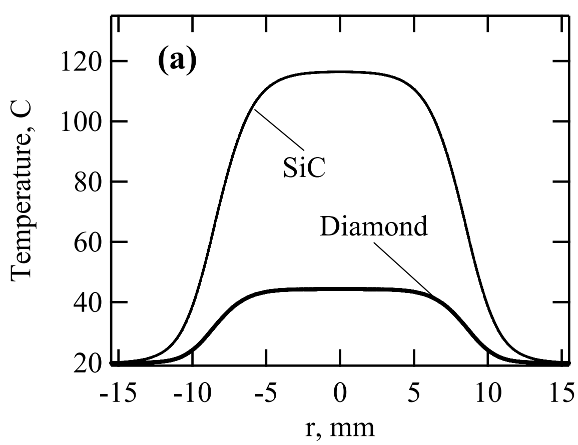

Figure 10 Modeled surface temperature in the radial direction for SiC and Diamond heat sinks

4. SUMMARY

The long term objective of Air Force Research Laboratory thin-disk work is towards high beam quality. Correspondingly this research, initially directed at generating high power lasers, turned towards thermal management problems. Mitigating these issues leads to minimization of disk deformation, improvement in overall efficiency, and increases in the total laser power. A further necessary step in this direction pertains to understanding all aspects of thin-disk lasers. physics-based research is being conducted regarding small signal gain, amplified spontaneous emission, and thermal issues. Mechanical engineering problems focus on improvements in associated materials.

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